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Climatological Coefficients for Rain Attenuation at Millimeter Wavelengths

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CLIMATOLOGICAL COEFFICIENTS FOR RAIN ATTENUATION AT MILLIMETER WAVELENGTHS

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It is demonstrated that most of the classical raindrop-size distribution formulations give inconsistent results when used to calculate specific attenuations at millimeter-wave frequencies. For this reason, it was decided it might be desirable to subcategorize drop-size distributions on the basis of large-scale worldwide climatological zones. This was done in the belief that different distributions will be needed in different environments to produce more accuracy in predicting millimeter-wave rain attenuation for a given location.

Raindrop-size data taken over a span of about 40 years in these various climatic zones are discussed briefly in terms of common characteristics. Some empirical methods of drop-size distribution measurements are discussed, and 226 drop-size distributions are grouped broadly into four climatic zones and presented in terms of a well-known model drop-size distribution formulation.

Using these results, zonal coefficients for the standard specific attenuation-rain rate relationship are obtained by a couple of different least-squares regression procedures. While results are different from previous results, there is no distinct indication that they represent an improvement. A need for further work is then discussed.

Key words: climate zones; millimeter-wave frequencies; raindrop-size distributions; specific attenuation

1. INTRODUCTION AND BACKGROUND

The most classical approach of determining rain attenuation (Goldstein, 1951) has been to theoretically determine the specific attenuation for a single drop, using so-called "Mie Theory," and integrating this attenuation over the "dropsize distribution." The drop-size distribution, n(D), gives the number of drops, n(D)dD, with diameters between D and D+dD. Thus, if terminology were consistent with probability theory, n(D) would have the nomenclature "drop-size density function," and some confusion might be avoided. In this classical approach, drop-size distribution is then related to rain rate, R, measured in millimeters per hour, so that specific attenuation (attenuation per unit length) can also be related to R (Olsen et al., 1978). The preponderance of rain attenuation analysis has been concentrated

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at microwave frequencies (<15 GHz), and use of certain "standard" drop-size distributions has come to be acceptable practice in this frequency region.

The most commonly used drop-size distributions are the Laws and Parsons (LP) distribution (Laws and Parsons, 1943), the Marshall-Palmer (MP) distribution (Marshall and Palmer, 1948), and the Joss distributions (Joss et al., 1968). The Joss distributions consist of a "drizzle" distribution (JD), a "widespread rain" distribution (JW), and a thunderstorm distribution (JT). Except for the LP distribution, all these distributions can be written in an exponential form; viz.,

$$n(D,R) = N_0 \exp[-\Lambda(R)D] \quad . \tag{1}$$

In (1), $n(D,R)$ is the drop-size distribution, N_0 is a constant, depending upon the distribution, and $\Lambda(R)$ is a power function of R.

As application of rain attenuation prediction is extended above 15 GHz and into the millimeter-wave region, however, Figure 1 shows the behavior with increasing frequency of attenuation predicted from the standard distributions. Figure 1 is a plot of specific attenuation in decibels per kilometer versus frequency in gigahertz for the MP, JT, and LP distributions for a fixed rain rate, R = 68.7 mm/hr. The significant aspect about Figure 1 is the rather rapid divergence and lack of comparability with frequency of three curves representing specific attenuation for the MP, JT, and LP distributions. Thus, it is more likely that an arbitrary choice of one of the standard drop-size distributions will not suffice as representative of a given scenario. As a consequence, it may become necessary to obtain drop-size distributions on a climatological basis. In this report, we have endeavored to categorize drop-size distributions (Section 2) and then specific attenuation (Section 3) on a macroscale climatological basis for use at millimeter-wave frequencies.

The macroscale subdivision of world climates chosen here is that of Köppen (1918). There are five basic climate types (A, B, C, D, and E) as shown in Table 1. It is these five major world climatic subdivisions that we have chosen to work with throughout this report.

2. DROP-SIZE DISTRIBUTION DATA AND ANALYSIS

Raindrop-size distribution data have been taken by such diverse groups as agricultural engineers, soil engineers, meteorologists, and communication engineers for several decades. Perhaps the earliest formal effort in drop-size measurement was made by Weisner (1895), who observed the sizes of spots left on absorbent

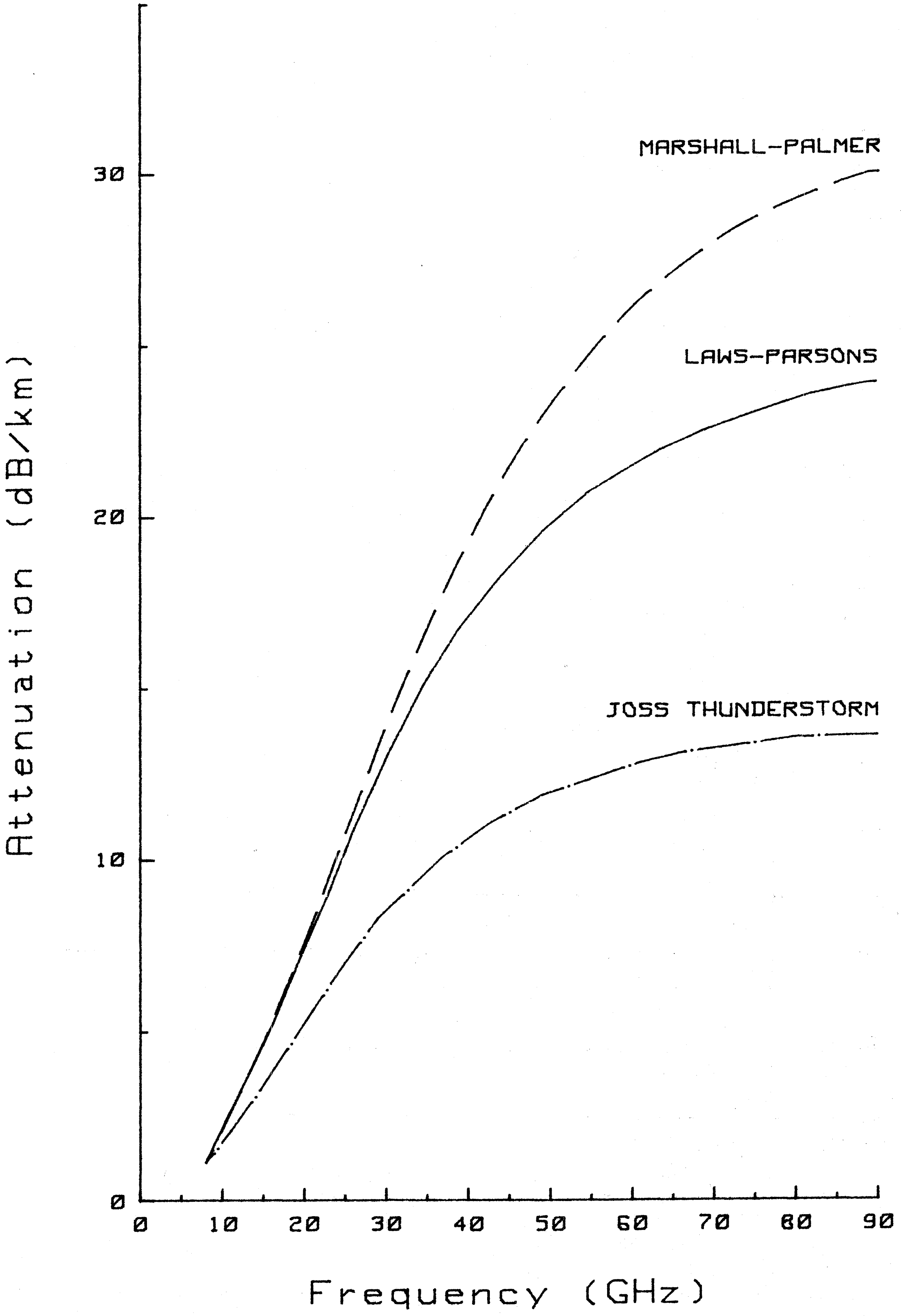

Figure 1. Variation of specific attenuation for different drop-size distributions at Washington, D.C., for rain-rate conditions expected 0.01 percent of an average year.

Table 1. Köppen's Worldwide Climatic Classification

Climatic Type	Characteristics	Examples
A Climates	Moist Tropical Climates	
Af	no dry season	Many islands in the Pacific Ocean, Indonesia, Central America
Aw	distinct dry season	Most of Southeast Asia, Northern Philippines, India
B Climates	Arid Climates	
BW	desert climates	Southwest CONUS, Most of Southwest Asia, Some of Australia
BS	steppe climates	Western CONUS, parts of Australia, southern U.S.S.R.
C Climates	Warm Temperate Rainy Climates	
Cf	more than 0.5 in. of precipitation in driest month	South Korea, Okinawa, Germany, much of Europe and U. K.
Cw	has a winter dry season	Large parts of China
Cs	has a summer dry season	Parts of the Middle East, Spain, Turkey, California Coast
D Climates	Cold Temperate Climates	
Df	more than 0.5 in. of precipitation in driest month	Northern CONUS, Southern Canada, Much of U.S.S.R. and Alaska
Dw	has a winter dry season	Parts of Siberia
E Climates	Polar Climates	
Et	tundra climates	Northern Alaska, Northern U.S.S.R.
Ef	perpetual frost climates	Greenland

paper by raindrops. In a more modern era, coincident with the development of microwave systems, among other things, the level of interest in raindrop sizes has grown, and the measurement techniques have become more sophisticated. This report will concentrate on raindrop-size distributions observed during the last four decades. We will briefly consider some empirical methods and data characteristics and present the observations as model coefficients for use in different climatic zones by millimeter-wave and microwave systems designers.

A short bibliography is included with the references for the interested reader.

2.1 Brief Discussions of Some Empirical Methods of Drop-size Measurement

The absorbent paper-water soluble dye method was developed by Weisner (1895). Absorbent paper, dusted with dye, was exposed to rainfall. The drop-spots were thus permanently recorded and could be sized by calibration with known drop sizes and counted. The basic method has been used even recently. Niederdorter (1932) identified significant errors associated with the splatter of large drops.

Bentley (1904) introduced the flour/powder method of drop-size measurement. With this technique, a surface of smooth, uncompacted flour was exposed to rainfall for a short time. The dough-pellets formed were size-related to raindrop diameters. The method produced interesting results; however, Laws and Parsons (1943), reported that small drops were often missed.

A photoelectric drop-size spectrometer was developed by Dingle and Schulte (1962). The device has a light beam and a photometer which receives light scattered from raindrops in an amount proportional to drop size.

Jones and Dean (1953) constructed the drop camera. It was triggered automatically by rain to photograph falling drops. It could sample about one cubic meter of space per minute and detect drops from about 0.4 mm to 8.0 mm in diameter. The data were reduced by hand.

An impact disdrometer was introduced by Joss and Waldvogel (1967). The device electromechanically measures the momentum of impacting raindrops. With the measured momenta and the terminal drop velocities of Gunn and Kinzer (1949), it is possible to determine drop diameters. The method gives consistent results and is in wide use today. It should be noted, however, that Donnadieu (1980) reported terminal velocities as much as 10 percent different from those of Gunn and Kinzer (1949).

The final drop-size measurement technique to be considered here is that of Ugai (1977). The technique is to use water-soluble blue dye suspended in a layer of castor oil. Raindrops fall into the oil, absorb the blue dye, and sink to the bottom where they can be photographed and counted. Finally, the size distributions (in a volume of air) are ascertained by dividing the measured drop sizes (on the surface) by the terminal drop velocities of Gunn and Kinzer (1949). The distributions determined by this method are similar to those of other methods if only drop diameters of 1 mm or so and greater are considered. However, when only very small drops are considered, the indicated drop numbers may be as high as a few hundred thousand ($m^{-3}mm^{-1}$) for the higher rain rates.

It is apparent from these measuring techniques that drop diameters <1 mm are not well determined. However, larger diameter drops have more consistent distributions.

2.2 Discussions and Results

Manual and automated literature searches yielded 78 articles (see Section 5) pertaining to raindrop-size measurement methods or data. There are some noteworthy, obvious characteristics of the data when they are displayed on semilogarithmic plots. First, there are three common basic distribution shapes. These are the concave downward distribution (see Figure 2), typical of the data of Mueller and Sims (1967a, 1967b, 1968a, 1968b); the linear distribution (see Figure 3), typical of Marshall and Palmer (1948); and the concave upward distribution (see Figure 4), typical of the data of Ugai (1977). Nearly all the distributions tend toward linearity when drop diameters greater than about 1 mm are considered. Second, the linear portions of the drop-size curves exhibit slopes which tend to be related to rain rates, and the raindrop densities ($m^{-3}mm^{-1}$) are similar (about 100 to 3000) for similar rain rates. Third, the measured drop densities at diameters less than about 1 mm show wide disparities. For example, Ugai (1977) in Tokyo, observed about 5000 drops ($m^{-3}mm^{-1}$) of about 0.5 mm in diameter at a rain rate of 46.4 mm/hr^{-1} while Furuhama and Ihara (1981), also in Tokyo, observed about 100 drops ($m^{-3}mm^{-1}$) of about 0.5 mm in diameter at a rain rate of nearly 90 mm/hr^{-1}. We shall therefore deal only with drop diameters of about 1 mm and greater for the remainder of this report. Unfortunately, this leaves the small-drop effect on the specific attenuation coefficients derived in Section 3 unresolved at this time.

Marshall and Palmer (1948) found that raindrop-size distributions could be modeled by an expression of the form given by (1). In (1),

$$\Lambda(R) = cR^{-d}(mm^{-1}) \quad , \tag{2}$$

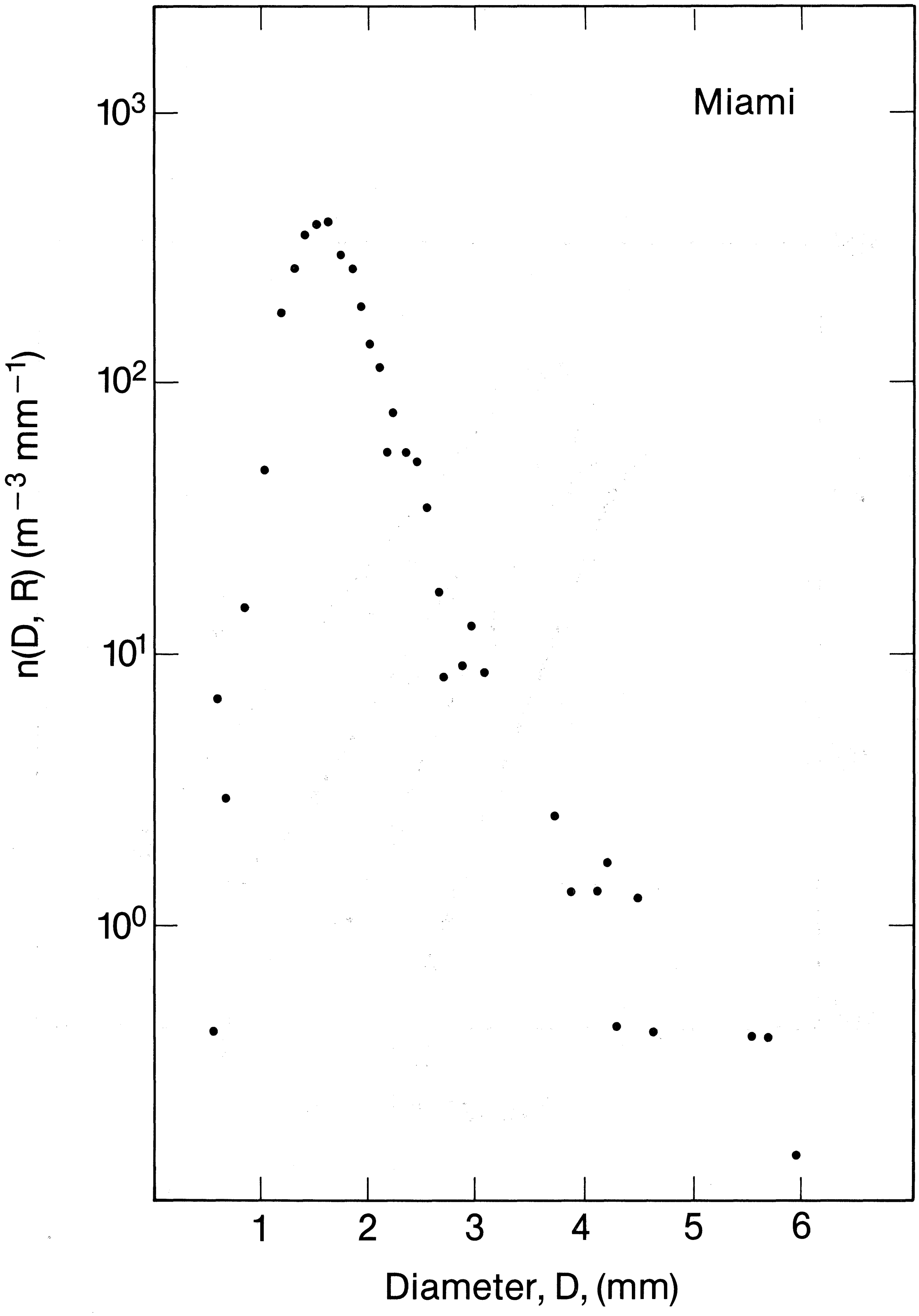

Figure 2. Distribution of raindrop sizes versus diameter for raindrops recorded at Miami, Florida, at a rainrate, R=20 to 25 mm/hr [after Fang and Chen (1982)].

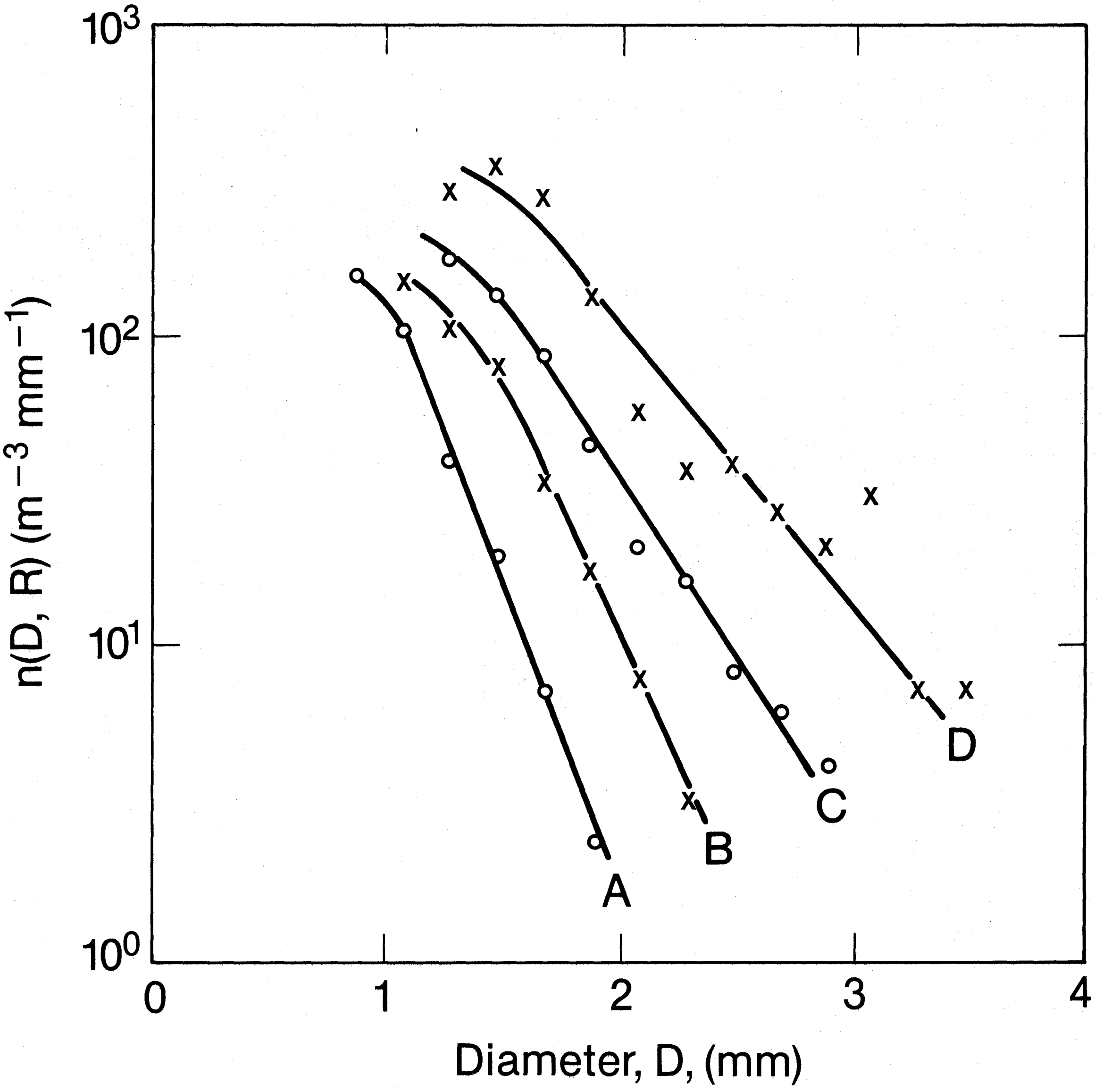

Figure 3. Distribution of raindrop sizes versus diameter for raindrops recorded at Ottawa, summer 1946 [after Marshall and Palmer (1948)].

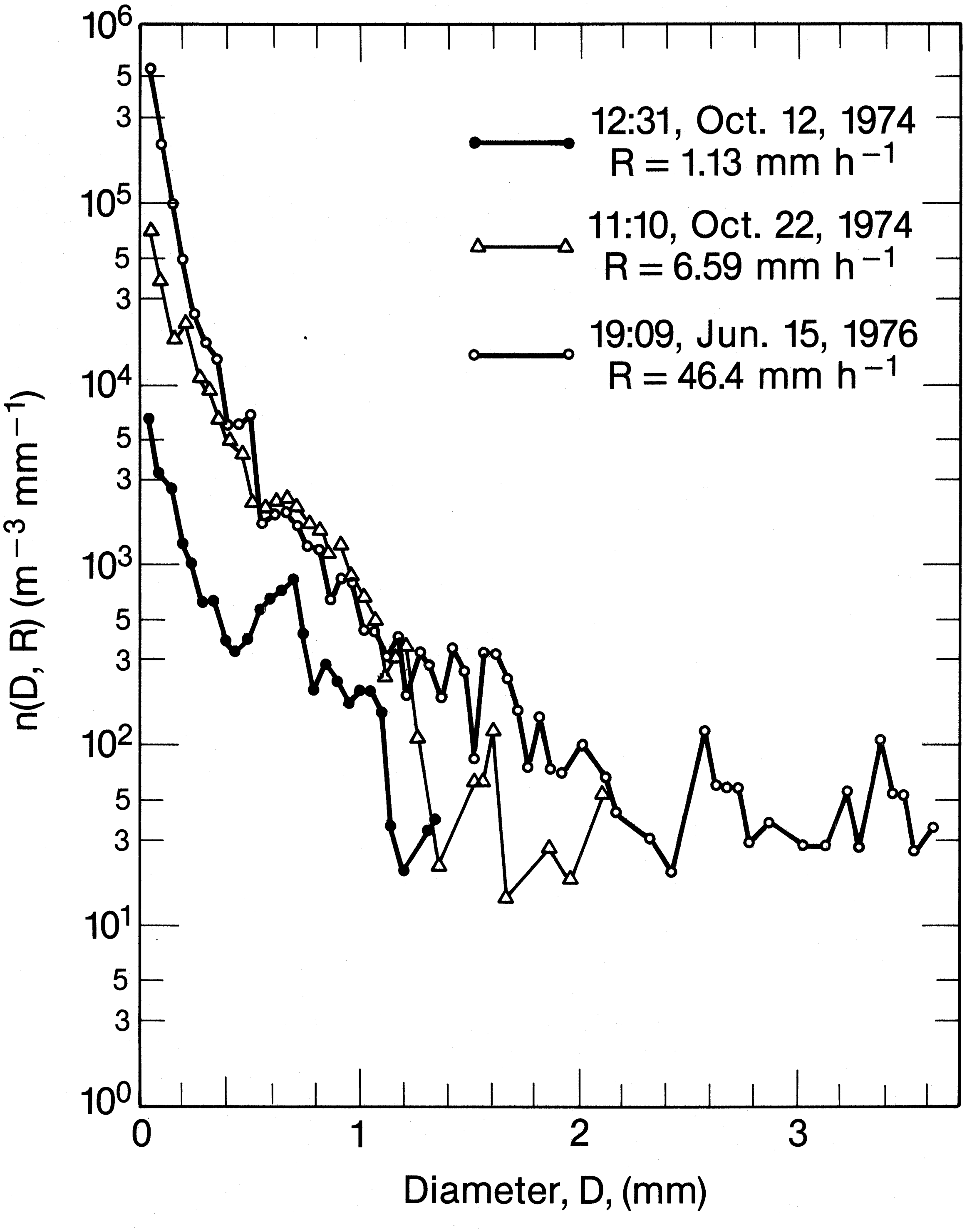

Figure 4. Distribution of raindrop sizes versus diameter for raindrops recorded in Tokyo, Japan, at the times and rainrates, R, indicated [after Ugai (1977)].

where R = rain rate (mm/hr^{-1}), and c and d are constants. For the Marshall and Palmer (1948) data, $N_0 = 8000\ m^{-3}mm^{-1}$ in (1), while c = 4.1 and d = 0.21 in (2).

Measurement locations have been classified in terms of major Köppen (1918) climatic zones and are given in Table 2. Data from the various climatic zones were carefully examined and four lines of best fit (by eye) were established to zonally lumped data for drop diameters of 1 mm and above.* From these lines, N_0 and $\Lambda(R)$ were determined. There appears to be a relation between $\Lambda(R)$ and rain intensity, but no discernible relation between N_0 and rain intensity for the lumped data. Before definite conclusions are drawn, however, it is desirable to have more data and to make regression fits to all the data for each climatic zone. These findings do parallel those of Joss et al. (1968), but Wickerts (1982) found that N_0 was related to rain rates in Sweden.

The estimated values for N_0 and $\Lambda(R)$ for the lumped data of Köppen (1918) zones A, B, C, and D are shown in Table 3. Column 1 gives the climatic zone classification while the number of experimental values is shown in column 2. The average N_0 for each of the zones is shown in column 3, while the standard deviation of N_0 is given in column 4. Finally, $\Lambda(R)$ (estimated by least-squares fit) is shown in column 5, and its standard error of estimate is given in column 6. It is interesting to note that Joss et al. (1968) report mean N_0 to be 1400, 7000, and 30,000 ($m^{-3}mm^{-1}$) and $\Lambda(R)$ to be $3.0\ R^{-.21}$, $4.1\ R^{-.21}$, and $5.7\ R^{-.21}$ (mm^{-1}) for thunderstorm and widespread and drizzle rain types, respectively. Further, they found that N_0 can vary from 300 to 100,000 ($m^{-3}mm^{-1}$) in one rainfall. Caimi and de Menzies (1978) report that in Argentina the standard deviation of N_0 can vary between rainfalls from 356 to 19,154. This variation is even greater than the variation in the standard deviation of N_0 as shown in column 4. Some drop-size researchers did not delineate their results on the basis of rain type. The values for model parameters N_0 and $\Lambda(R)$ shown in Table 3 are, in general, in order-of-magnitude agreement with individual findings of others, notably with Joss et al. (1968) and Marshall and Palmer (1948). The paucity of data for regions B and D is disappointing; however, there are more data for regions A and C.

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*Note that the lumped zonal results in Table 3 were not used to obtain specific attenuation results obtained in the next section. The attenuation results were obtained from the 226 individual distribution results in the four Köppen zones.

Table 2. Drop-size Measurement Locations (Köppen (1918) Zone)

(A) (Tropical Rainy)		(B) (Dry)	
Location	Observer	Location	Observer
China	Li and Chang (1980)	Arizona, USA	Alkezweeny (1971)
Hawaii	Blanchard (1953)	China	Li and Chang (1980)
India	Sivarama, Krishnan, and Selvam (1965)	Colorado, USA	Danielson and Huggins (1974)
Indonesia	Mueller and Sims (1968b)	Texas, USA	Carbone and Nelson (1979)
Majuro	Mueller and Sims (1967b)		
Panama	Geotis (1969)		
(C) Humid Mesothermal		(D) (Humid Microthermal)	
Alabama, USA	Plank et al. (1980)	Canada	Marshall and Palmer (1948)
Argentina	Caimi and deMenzies (1978)	N.E.Colorado,USA	Martner (1975)
England	Caton (1966)	Michigan, USA	Dingle and Hardy (1962)
"	Illingworth (1981)		
"	Mason and Andrews (1960)		
"	Mason and Ramanadham (1953)		
France	Donnadieu (1980)		
Japan	Furuhama and Ihara (1981)		
"	Shiotsuki (1974)		
"	Uchida and Ohta (1979)		
"	Ugai (1977)		
Korea	Shiotsuki (1975)		
New Jersey,USA	Mueller and Sims (1967a)		
North Carolina USA	Mueller and Sims (1967c)		
Massachusetts USA	Geotis (1968)		
"	Gori and Geotis (1981)		
Oregon, USA	Mueller and Sims (1968a)		
Switzerland	Federer and Waldvogel (1975)		
"	Gori and Joss (1980)		
"	Joss and Gori (1978)		
Sweden	Wickerts (1982)		
Virginia, USA	Plank et al. (1980)		

Table 3. Estimated Model Parameters

1 Köppen (1918) Zone	2 Number of points	3 Average N_o	4 Standard Deviation of N_o	5 $\Lambda(R)$ (Regression)	6 Standard Error of Estimate $\Lambda(R)$
A	53	4631	4612	$4.0\ R^{-.16}$	.5905
B	16	5043	3479	$3.8\ R^{-.08}$	.6210
C	145	6977	13468	$3.5\ R^{-.19}$	.3011
D	12	4560	3265	$3.4\ R^{-.24}$	.8862

3. ZONAL ATTENUATION COEFFICIENTS

In the preceding section, 226 drop-size distributions resulted from the available literature on the subject. These drop-size distributions were then catalogued according to the macroscopic climatological subdivision of the world given by Köppen (1918) as in Table 1. It was determined that 53 of these distributions applied to zone A, 16 to zone B, 145 to zone C, 12 to zone D, and none to zone E. Zone E is the polar climates category and includes a largely uninhabited area of the world.

These drop-size distributions can be individually fitted with an exponential distribution of the form of (1). The fitting procedure was an "eyeball" fit, analogous to the fitting of the zonal lumped data discussed in Section 2.2. Also, as in Section 2.2, N_o is essentially a constant for a given individual data distribution, but $\Lambda(R)$ is also a constant for an individual data distribution because the rain rate, R, has a fixed value for a given individual distribution.

3.1 Specific Attenuation

In order to relate specific attenuation and raindrop-size distributions, use can be made of the following relationship:

$$\alpha(f,R) = 8.6858 \frac{c^2}{2\pi f^2} \int_o^{D_m} n(D,R) \mathrm{Re}[S_o(f,D)]\, dD \quad . \tag{3}$$

In (3),

$\alpha(f,R)$ = signal attenuation in decibels per unit length (or specific attenuation),

$n(D,R)$ = an individual data drop-size distribution fitted to the form of (1),

c = free-space speed of light,

f = signal frequency,

D = diameter of a spherical raindrop,

$S_0(f,D)$ = forward scattering function evaluated from Mie theory, and

D_m = maximum expected raindrop diameter (assumed = 6.0 mm).

Correspondingly, then, an array of 226 specific attenuations can be evaluated for the 226 fitted exponential drop-size distributions with 53 in zone A, 16 in zone B, 145 in zone C, and 12 in zone D, at a given frequency, f. Since there are several specific attenuations, $\alpha(f,R)$, in a given zone, scatter diagrams of $\alpha(f,R)$, at a given frequency, can be developed of $\alpha(f,R)$ versus R. As we shall see, it will also be desirable to have scatter diagrams of α versus log R and log α versus log R.

In order to make use of these scatter diagrams, let us consider a specific attenuation relationship: namely, the classical

$$\alpha_z(f,R) = a_z(f)R^{b_z(f)} \quad , \tag{4}$$

where $\alpha_z(f,R)$ will represent a zonal (z) average relationship obtained by statistical regression techniques applied to given zonal data at a given frequency. The values $a_z(f)$ and $b_z(f)$ then represent coefficients derived from the regression fits. The form of (4) is a quasi-empirical relationship [in spite of the "theoretical" derivation of Olsen et al. (1978)], but we are using this particular form because it is relatively simple to fit, and it is the most widely used specific attenuation relationship.

Figure 5 shows a sample scatter diagram for zone A at a frequency of 30 GHz of $\alpha(f,R)$ versus R. In addition, the regression curve of the form of (4) for these data is shown on Figure 5. One salient aspect of Figure 5 is the "ball" of data that occurs near the origin, representing low rain rate-low attenuation data, with only a few of the total 53 points having any spread whatsoever. This apparent lack of trend in Figure 5 can be resolved if we plot $\alpha(f,R)$ versus $\log_{10}R$, as in Figure 6, for the same conditions as in Figure 5. Now, in Figure 6, one can more easily see the trend of the data which were fit with a curve of the form

$$\alpha_z(f,R) = a_z(f)10^{b_z \log_{10} R} \quad . \tag{5}$$

Of course, (5) and (4) are exactly the same equation, even insofar as a least-squares process is concerned (see the Appendix), but the regression fit of (5)

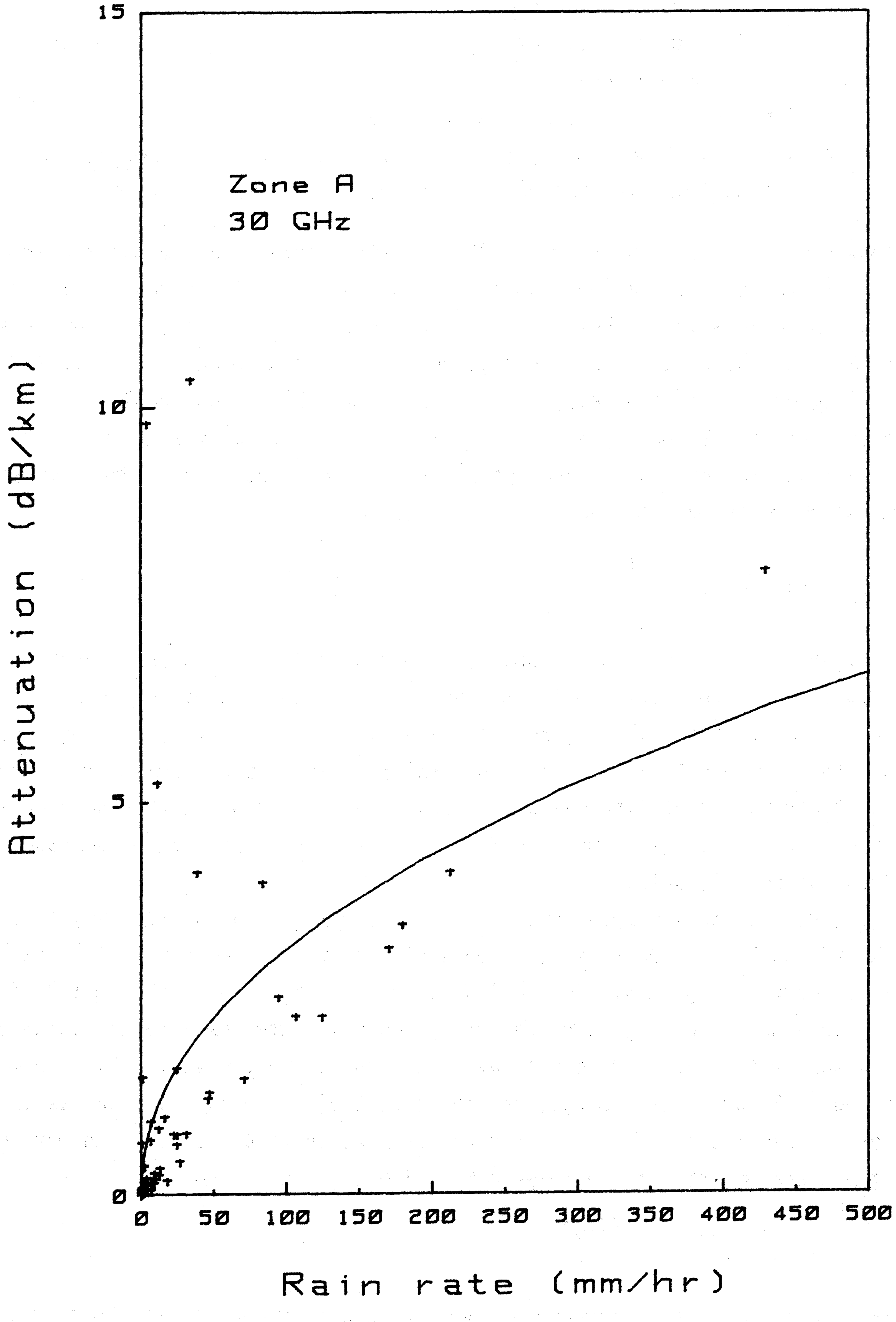

Figure 5. Specific attenuation data and regression curve using equation (4) for climatic zone A at 30 GHz.

through the data of Figure 6 gives the reader a clearer picture of the fit-data relationship. Figure 7 shows a scatter diagram of $\log_{10}\alpha(f,R)$ versus $\log_{10}R$ for the same conditions as in Figures 5 and 6. A least-squares fit through these data of the form

$$\log_{10}\alpha_z(f,R) = \log_{10}a_z(f) + b_z(f)\log_{10}R \qquad (6)$$

is also shown on Figure 7. Since (6) is a somewhat different least-squares process (see the Appendix) than (4) or (5), the resultant $a_z(f)$ and $b_z(f)$ are different for the regression fit of (6) as compared with those of (4) and (5). Although the literature is not clear on this point, it is most likely that the linear regression form of (6) has been the historical procedure for determining the coefficients in a power-law fit, rather than procedures directly involving (4) or (5). Prior to the advent of computers when the Marshall-Palmer (1948) results were obtained, a procedure such as (6) would have been about the only practical way to proceed. Hence, one might expect that zonal results obtained from (6) would be more comparable with standard formulations, as indeed they appear to be in the next subsection of this report. This comparability, however, does not mean that results obtained using (6) are necessarily any better than those obtained using (4) or (5).

3.2 Zonal Coefficient Results

As has been indicated, data for statistical regression analysis exist in Köppen zones A, B, C, and D. The specific attenuations, $\alpha(f,R)$, representing data in each zone, were evaluated from (3). The expression (3) is evaluated for each data point by the numerical integration technique of Gaussian quadrature for drop sizes ranging from zero to 6.0 mm in diameter. In a few cases the maximum diameter slightly exceeds 6.0 mm, but it is not enough to make any difference in the final numerical integration result.

Tables 4, 5, 6, and 7 show results of the regression fits of the forms of (4), (5), and (6) for zones A, B, C, and D, respectively. In each of the tables, the zonal coefficients $a_z(f)$ and $b_z(f)$ are given for the regression fits, along with the standard error of estimate, S.E., of the fit. Coefficient results are tabulated for five frequencies--10, 30, 60, 100, and 300 GHz. The behavior of $a(f)$ and $b(f)$ in traditional models, such as for the Marshall-Palmer drop-size distribution, shown in Tables 4 through 7 for comparison, is generally smoothly declining between 10 and 30 GHz. Because of this fact, it is assumed that a smooth, curvilinear interpolation (such as exponential) can be made to determine values of

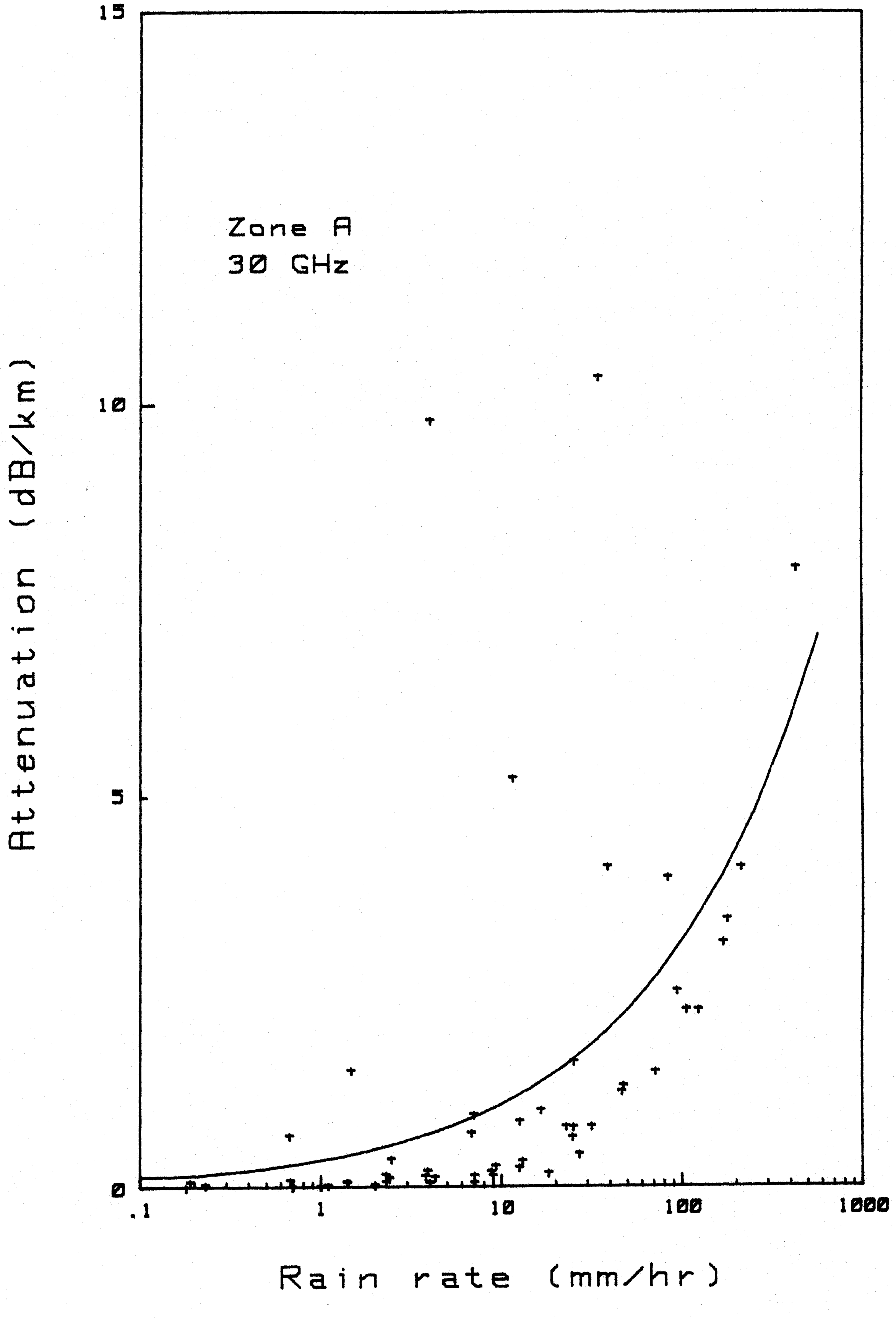

Figure 6. Specific attenuation data and regression curve using equation (5) for climatic zone A at 30 GHz.

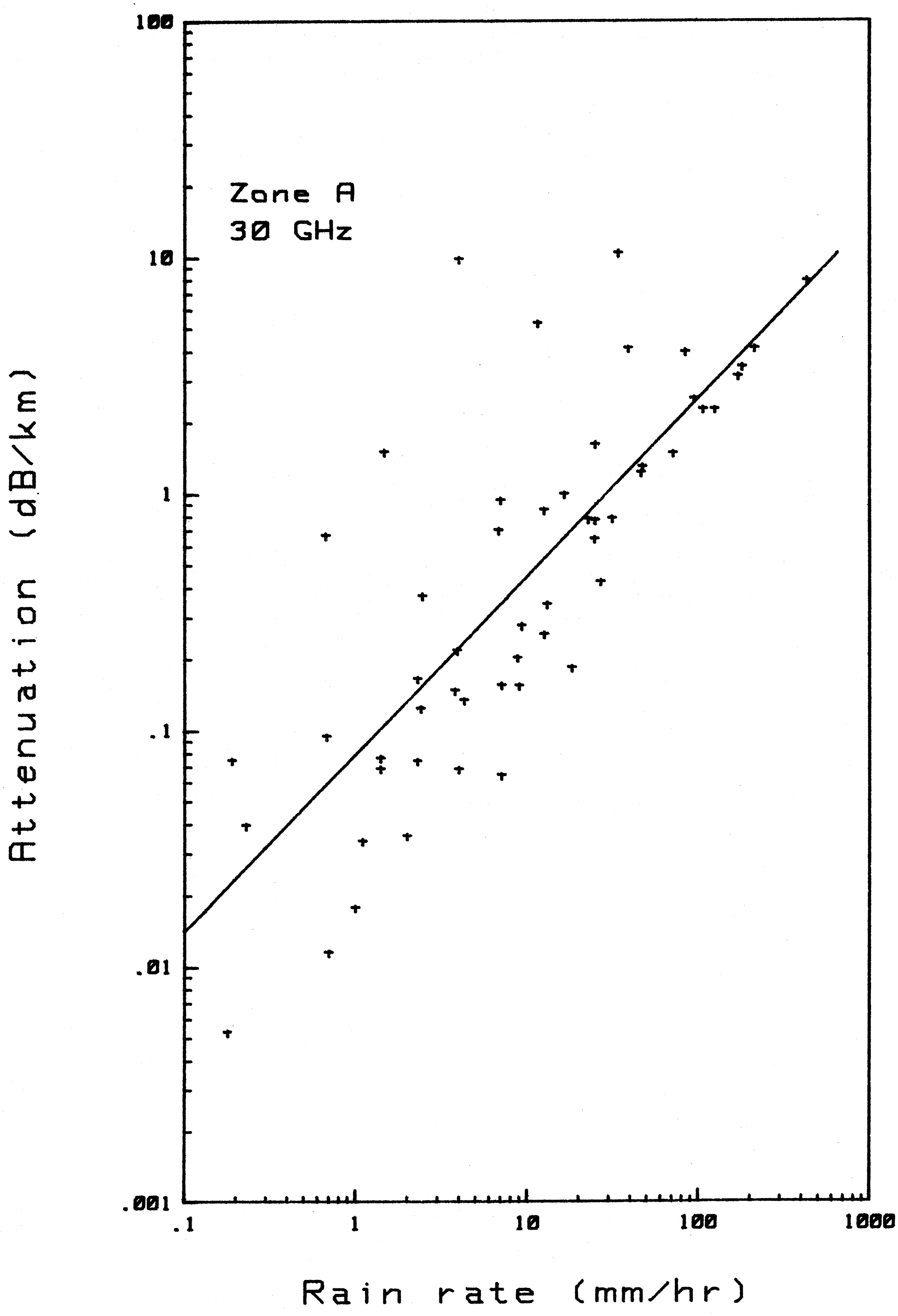

Figure 7. Specific attenuation data and regression curve using equation (6) for climatic zone A at 30 GHz.

Table 4. Coefficients for Zone A of the Relation

$$\alpha_z(f,R) = a_z(f)R^{b_z(f)} \pm S.E.$$

Frequency (GHz)	Evaluated from (4) or (5)			Evaluated from (6)			Olsen et al.'s values using the MP distribution at 0°C	
	$a_z(f)$	$b_z(f)$	S.E.	$a_z(f)$	$b_z(f)$	S.E.	a (f)	b (f)
10	3.45×10^{-2}	0.536	0.290	4.72×10^{-3}	0.899	0.300	1.36×10^{-2}	1.150
30	0.370	0.465	2.00	8.66×10^{-2}	0.735	2.06	0.186	1.043
60	1.05	0.399	4.03	0.331	0.611	4.17	0.801	0.851
100	1.65	0.352	5.02	0.637	0.515	5.21	1.48	0.730
300	2.07	0.306	5.12	0.956	0.423	5.34	2.24	0.614

S.E. = standard error of estimate

Table 5. Coefficients for Zone B of the Relation

$$\alpha_z(f,R) = a_z(f)R^{b_z(f)} \pm S.E.$$

Frequency (GHz)	Evaluated from (4) or (5)			Evaluated from (6)			Olsen et al.'s values using the MP distribution at 0°C	
	$a_z(f)$	$b_z(f)$	S.E.	$a_z(f)$	$b_z(f)$	S.E.	a (f)	b (f)
10	1.95×10^{-5}	2.66	0.02	6.44×10^{-3}	0.937	0.09	1.36×10^{-2}	1.150
30	8.88×10^{-2}	0.917	0.17	1.14×10^{-2}	0.841	0.91	0.186	1.043
60	0.631	0.571	0.46	0.424	0.748	0.74	0.801	0.851
100	1.24	0.460	0.92	0.802	0.665	1.37	1.48	0.730
300	1.75	0.392	1.28	1.19	0.575	1.67	2.24	0.614

S.E. = standard error of estimate

Table 6. Coefficients for Zone C of the Relation

$$\alpha_z(f,R) = a_z(f)R^{b_z(f)} \pm \text{S.E.}$$

Frequency (GHz)	Evaluated from (4) or (5)			Evaluated from (6)			Olsen et al.'s values using the MP distribution at 0°C	
	$a_z(f)$	$b_z(f)$	S.E.	$a_z(f)$	$b_z(f)$	S.E.	a (f)	b (f)
10	9.72×10^{-2}	0.599	0.49	7.74×10^{-3}	1.224	0.64	1.36×10^{-2}	1.150
30	0.742	0.555	2.83	0.125	1.015	3.52	0.186	1.043
60	1.68	0.510	5.36	0.444	0.855	6.09	0.801	0.851
100	2.31	0.476	6.66	0.806	0.737	7.16	1.48	0.730
300	2.65	0.441	6.91	1.16	0.623	7.23	2.24	0.614

S.E. = standard error of estimate

Table 7. Coefficients for Zone D of the Relation

$$\alpha_z(f,R) = a_z(f)R^{b_z(f)} \pm \text{S.E.}$$

Frequency (GHz)	Evaluated from (4) or (5)			Evaluated from (6)			Olsen et al.'s values using the MP distribution at 0°C	
	$a_z(f)$	$b_z(f)$	S.E.	$a_z(f)$	$b_z(f)$	S.E.	a (f)	b (f)
10	9.13×10^{-3}	1.397	0.33	1.42×10^{-2}	1.149	0.57	1.36×10^{-2}	1.150
30	0.104	1.186	0.40	0.237	0.875	1.61	0.186	1.043
60	0.430	0.941	1.91	0.816	0.690	2.93	0.801	0.851
100	0.828	0.799	2.96	1.41	0.578	3.84	1.48	0.730
300	1.19	0.689	3.31	1.88	0.490	4.04	2.24	0.614

S.E. = standard error of estimate

coefficients for frequencies between 10 and 300 GHz, using the values given in Tables 4 through 7.

Two features of Tables 4 through 7 are worthy of note. First, the standard error of estimate, S.E., appears rather large. As can be seen from Figures 5, 6, and 7, a few "nonconforming" points seem to be the major contributors to the S.E.'s. Second, the zonal coefficient results obtained from the regression fits have only order-of-magnitude resemblance to the coefficients obtained by Olsen et al. (1978) using the MP distribution. The more traditional coefficients appear to be derived from a very select (i.e., small) data base. The same would be true of coefficients derived from the Laws and Parsons (1943) or the Joss et al. (1968) data bases.

4. CONCLUSIONS AND RECOMMENDATIONS

Raindrop-size data taken in four macroscale (Köppen, 1918) climatic zones have been examined. The examination shows considerable disparity in drop densities in the small drop sizes, but reasonable agreement when larger (greater than about 1 mm) drop diameters are considered. An existing drop-size model can be fitted to much of the data for the larger drop sizes; however, the model parameter N_0 shows a large variation, and it is apparently not related to rain rate. There is a paucity of data for arid and cold climates; fortunately, there is a larger data base for the more populated tropical and humid temperate climates.

On the basis of the macroscale subdivision of the world's climates, the drop-size distribution data in four of the five zones were used to develop zonal coefficients for the specific attenuation-rain rate relationship (4). The resulting coefficients do little to resolve any confusion that might exist in the millimeter-wave region as to which set of coefficients is truly meaningful. The results continue to indicate the random behavior of attenuation on a climatological basis, implying an existing need to assess variability and statistical bounds on any kind of relationship used for prediction purposes. As well, there is indicated a need for either a more consistent and meaningful climatological classification structure, or more data within the zonal classifications used in this report--or both. The one real conclusion of this report, that use of any of the modeled specific attenuation-rain rate relationships should be pursued with considerable caution at millimeter-wave frequencies, will perhaps stimulate endeavors to acquire more and meaningful rain attenuation/rain description data with the intent of providing usable prediction relationships.

As the need for millimeter/microwave communication links grows, it would be helpful to have more raindrop-size/rain-rate data for all climatic regions and to have more standardized research so that the results could be readily used by technical workers of diverse interests. It would be desirable to resolve the disparities in small drop density measurements and to standardize measurements by universal reporting of parameters such as location, rain rate, altitude, rain type, and any other factors which are generally considered to be relevant.

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APPENDIX. LEAST-SQUARE REGRESSIONS OF $A=kR^{\gamma}$

Given the current state of the art in computer least-squares analysis, finding coefficients to fit the $A=kR^{\gamma}$ model can be done three ways:

1) R vs. A, $f_1(x) = c_1x^{c2}$,
2) $\log_{10}$ R vs. A, $f_2(x) = c_1e^{c2x}$, and
3) $\log_{10}$ R vs. $\log_{10}$ A, $f_3(x) = c_1 \log_{10} R + c_2$,

where $f_j(x)$, j=1, 2, 3, is the model used in the regression. In 3), the regressed formula is $\log_{10} A = \log_{10} R + b$, which implies $A = 10^{c2} R^{c1}$. The least-squares technique involves finding coefficients c_1 and c_2 such that the sum

$$\sum_{i=1}^{n} (f(x_i) - y_i)^2$$

is minimized. Given that, in models 1) and 2), one chooses the same values for c_1 and c_2, it is apparent that $f_1(x)$ and $f_2(x)$ are then equivalent. Since the modeling functions are equivalent and the same data are used in the least-squares analysis, the results are the same.

However, this no longer holds true in 3). The least-squares sum to be minimized is now $\sum_{i=1}^{n} ((c_1 \log_{10} R_i + c_2) - \log_{10} A_i)^2$, which has both a different model and different data to incorporate. The model function $f_3(x)$ gives logarithms of the predicted values, and these are compared to logarithms of the data.

Predicted values that are fairly close to the observed data in model 3) are quite far away in models 1) and 2) and vice versa. Consider the regression $c_1 R^{c2}$ predicting a value of 10^{-1} whereas the actual data are 10^{-2}. This would give a small error. Taking logarithms of predicted values and data gives a residual of 1. On the other hand, there is little difference between the logarithms of, for example, 10 and 11, but a large one between 10^{11} and 10^{10}.

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It is demonstrated that most of the classical raindrop-size distribution formulations give inconsistent results when used to calculate specific attenuations at millimeter-wave frequencies. For this reason, it was decided it might be desirable to subcategorize drop-size distributions on the basis of large-scale worldwide climatological zones. This was done in the belief that different distributions will be needed in different environments to produce more accuracy in predicting millimeter-wave rain attenuation for a given location.

Raindrop-size data taken over a span of about 40 years in these various climatic zones are discussed briefly in terms of common characteristics. Some empirical methods of drop-size distribution measurements are discussed, and 226 drop-size distributions are grouped broadly into four climatic zones and presented in terms of a well-known model drop-size distribution formulation.

(continued on next page)

16. Key Words *(Alphabetical order, separated by semicolons)*

Climate zones; millimeter-wave frequencies; raindrop-size distributions; specific attenuation

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Using these results, zonal coefficients for the standard specific attenuation-rain rate relationship are obtained by a couple of different least-squares regression procedures. While results are different from previous results, there is no distinct indication that they represent an improvement. A need for further work is then discussed.

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